Automated Signal Processing System of High-Frequency Dynamic Measurements for Engine Diagnostics

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NASA's advanced propulsion systems have been undergoing extensive flight certification and development testing. This process involves large volumes of health monitoring measurements. Under the severe temperature, pressure, and dynamic environments sustained during operation, numerous major component failures have occurred resulting in extensive engine hardware damage and schedule impact. To enhance engine safety and reliability, detailed analysis and evaluation of the high-frequency measurement signals are mandatory to assess the propulsion system dynamic characteristics and operational conditions. An efficient and reliable automated signal processing system that can analyze large amounts of high-frequency dynamic measurements can provide timely assessment of engine performance and diagnosis. Such a system will reduce catastrophic system failure risks and expedite the evaluation of both flight and ground test data, thereby reducing launch turnaround time.

During the development of the Space Shuttle Main Engine (SSME), a hierarchy of advanced signal analysis techniques for mechanical signature analysis has been developed by NASA and ASRI for the improvement of safety and reliability for Space Shuttle operations. These techniques can process and identify intelligent information hidden in a measurement signal which is often unidentifiable using conventional signal analysis methods. By providing additional insight into the system response, the techniques can better identify well-hidden defect symptoms as well as

false alarm signatures. As a result, use of signal analysis techniques reduces false alarm/misinterpretation rates and greatly improves system reliability. These techniques have been tested using SSME static test and flight data and appear to be extremely promising for failure analysis and detection in other complex machinery. These advanced mechanical signature analysis techniques as shown in table 5 have been integrated into an advanced signal analysis library (ASAL) for use at MSFC's Structural Dynamics and Loads Branch on the operator interactive signal processing system (OISPS).

The mechanical signature analysis techniques in the ASAL library have been used extensively in supporting critical, day-to-day MSFC SSME project flight and test program operations. The detection and understanding of anomalous signatures and their physical implications is the most important function of the ASAL techniques. However, due to the highly interactive processing requirements and the volume of dynamic data

involved, such detailed diagnostic analysis is currently being performed manually which requires immense man-hours with extensive human interface. The advanced nonlinear signal analysis topographical mapping system (ATMS) utilizes a rule-based expert system to supervise a sequence of diagnostic signature analysis techniques in the ASAL library in performing automatic signal processing and anomaly detection/identification tasks in order to provide an intelligent and fully automated engine diagnostic capability.

Figure 51 shows the logic flow of the overall ATMS system. Typical input to the system for SSME ground tests contains 60 to 80 channels of dynamic data at a sample frequency of 10,240 Hz for a test duration of approximately 550 sec. SSME flight data inputs range from 24 to 36 dynamic channels sampled at 10,240 Hz for approximately 520 sec. The interfaces between the CLIPS expert system and the ASAL programs were developed first. A set of ASAL execution rules of how to perform

TABLE 5.—*ATMS Advanced Signal Analysis Library (ATMS–ASAL).*

- Auto/Cross Bi-Spectral Analysis for quadratic nonlinear correlation identification
- Auto/Cross Tri-Spectral Analysis for cubic nonlinear correlation identification
- Hyper-Coherence Analysis for harmonic correlation identification
- Hyper-Coherence Filtering for waveform enhancement
- Instantaneous Frequency Correlation for frequency synchronous correlation analysis
- Micro-Frequency Cross Correlation technique for time delay estimation
- Composite-Modulation Analysis for higher order nonlinear correlation identification
- Phase Synchronous Enhancement Method for spectral resolution enhancement
- Coherent Phase Wideband Demodulation for cavitation detection
- Synchronous Time Averaging for waveform enhancement with keyphasor data
- Synchronous Phase Averaging for waveform enhancement without keyphasor data
- Rotary Spectral Analysis for dynamic orbit analysis
- Adaptive Comb/Notch Filter for dynamic orbit enhancement
- Recursive Least Square adaptive filter for adaptive noise cancellation
- Phase Domain Average technique for signal discreteness determination
- Topographical Algorithm for signal mapping and compression
- High-frequency Envelope Analysis for bearing fault detection
- Modified Wigner Distribution for high-resolution spectral analysis without cross-coupling
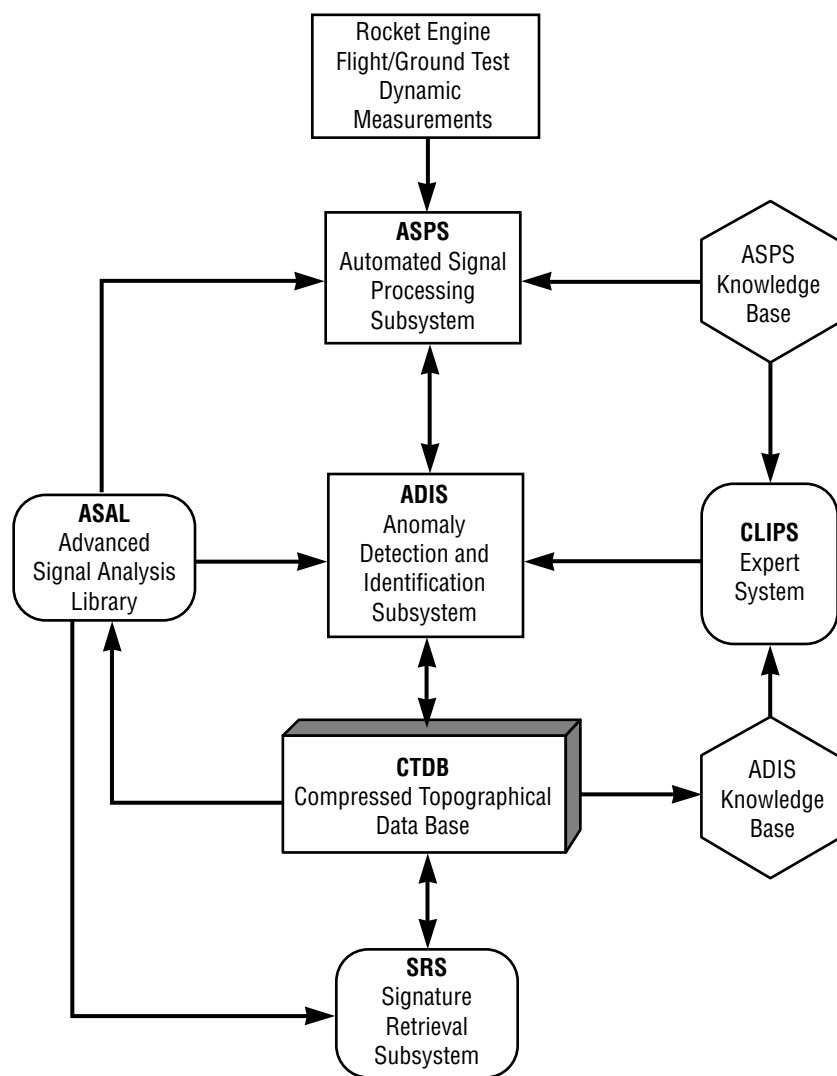
FIGURE 51.—ATM system logic flow.

capabilities which allows the entire engine test history to be readily accessible.

The ADIS is the most intelligent element of the ATMS. Its major function is to first detect the existence of any anomaly in the CTDB data base created by ASPS. Anomaly identification will then be performed in order to determine the physical underlying cause of the anomaly. The signature analysis techniques in ASAL can often provide valuable insight about the source of an anomaly and identify its underlying causes. Table 6 lists the typical anomaly detection and identification capabilities offered by ASAL for engine diagnostic evaluation. This anomaly detection and identification task requires interactive processing of various signal analysis techniques in ASAL. An ADIS knowledge base (ADIS-KB) was designed and established by extracting the knowledge and thought logic of experienced human experts in performing such anomaly detection/ identification, and reducing them into a set of rules for expert system execution. The ADIS then utilizes the CLIPS expert system to automate an intelligent ADIS analysis task by performing an extensive and highly interactive analysis for anomaly detection and identification.

A typical example of the ADIS logic flow will now be given. If a strong anomaly is detected at some frequency in the acceler-ometer data from the SSME high-pressure fuel turbopump (HPFTP), the ADIS will perform a sequence of appropriate signal analyses in order to identify the potential sources of this anomaly as:

- A high vibration level at the HPFTP synchronous and/or harmonic frequency due to rubbing, imbalance, misalignment, or instability;
- A bearing defect (inner race defect, outer race defect, rolling element defect) characteristic frequencies of various ball/ roller bearings (pump-end ball (PEBB), turbine-end ball (TEBB), turbine-end roller ball (TERB));
- A modulation/sideband spectral compo-nent of a bearing fault pattern;

the analysis of each ASAL program with correct parameter settings were established in the automated signal processing subsystem (ASPS) knowledge base (ASPS-KB). Based on this knowledge base, the ASPS then utilizes the CLIPS expert system to supervise the ASAL in performing a sequence of standard analysis tasks for engine postflight/test evaluation. The ASPS will automatically convert high-frequency dynamic signals from the engine opera-tional run into a bank of succinct image-like patterns in a compressed topographical format and other various special formats to be stored in the compressed topographical data base (CTDB). The results of the ASPS operations thus provides the basic fact data base and key statistic information for more detailed analysis in the subsequent anomaly detection and identification subsystem (ADIS). In addtion, the signature retrieval subsystem (SRS) can be enacted to provide fast signature retrieval, trending, and fault-pattern comparison/identification

TABLE 6.—*ATMS–ADIS anomaly detection/identification capabilities.*

- Detect nonlinear modulation/sideband phenomenon associated with bearing fault mechanisms
- Detect wideband modulation phenomenon associated with cavitation-induced vibration
- Identify feed-through or resonance from neighboring equipment
- Identify RPM/harmonics interference/overlap within a multi-rotor system
- Discriminate rotor-related vibration from independent nonrotor-driven source/noise
- Identify syncronous (RPM) modulated spectral component associated various nonlinear vibration mechanisms (including mechanical-driven) such as deadband interaction, and fluid-driven such as cavitation-induced asynchronous vibration, etc.
- Identify pure-tone electric line noise
- Identify structural/acoustical resonant mode
- Detect Frequency Modulation (FM) phenomenon associated with various FM vibration mechanisms such as shaft torsional vibration or gearbox transmission error
- Identify signal source through time-delay estimation
- Improve the signal-to-noise ratio in the vibration measurement data corrupted by noise
- Enhance spectral resolution for all RPM-related vibration components

- A synchronous/harmonic frequency feed-through from other engine turbopumps;
- Aliasing;
- An electrical line noise;
- A cavitation-induced vibration; or
- A structural mode, etc.

If the anomaly cannot be absolutely identified, ADIS will then try to identify certain dynamic characteristics associated with the anomaly such as:
- Whether it is synchronous frequency related or synchronous-independent;
- The anomaly modulation relationship with synchronous;
- The discreteness of the anomaly; or
- The instantaneous frequency/amplitude characteristics (periodic or random) of the anomaly, etc.

Preliminary testing of ATMS using actual SSME test data has demonstrated that the ATMS can perform detailed dynamic data analyses of large volumes of dynamic data without human interface thereby reducing the analysis man-hours. ATMS has also been used to support anomaly/incident investigations for the advanced turbopump (AT) HPFTP program and the information obtained was instrumental in the redesign of the AT/HPFTP hardware.

ATMS will significantly reduce manpower requirements for processing and analyzing large volumes of rocket engine flight/test dynamic data for diagnostic and performance evaluation. ATMS will allow NASA engineers to quickly evaluate rocket engine operational conditions of flight/test data, thereby reducing launch turnaround time and enhancing flight safety and reliability. ATMS will provide timely assessments of the engine performance, identify probable causes of malfunction/anomalies, and indicate feasible engineering solutions to enhance engine performance. In addition, failure history, fault symptoms, and anomalous signatures created in the CTDB will provide a foundation for future propulsion development programs.

An intelligent and fully automated rocket engine diagnostic system has considerable commercial application potential outside the NASA's propulsion area. Such a system would greatly increase the performance of monitoring and providing diagnostic data for critical mechanical/drive-train components of many industrial systems used by power plants, transportation, and manufacturing sectors.

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Biographical Sketch: Tony Fiorucci is an aerospace engineer with the Structural Dynamics and Loads Branch of the Structures and Dynamics Laboratory at Marshall Space Flight Center. He specializes in evaluation and characterization of vibration environments for both flight and ground test propulsion systems supervised by MSFC. His current and primary tasks include assessment/qualification of all vibration data acquired in support of the development, certification, and flight programs for the SSME project. Fiorucci graduated with a B.S. in engineering mechanics from the University of Tennessee in 1988.